

# Further considerations on layer-oriented adaptive optics for solar telescopes

Aglaé Kellerer

*Durham University,  
South Road, Durham, UK  
a.n.c.kellerer@durham.ac.uk*

The future generation of telescopes will be equipped with multi-conjugate adaptive optical (MCAO) systems in order to obtain high angular resolution within large fields of view. MCAO comes in two flavors: star- and layer-oriented. Existing solar MCAO systems rely exclusively on the star-oriented approach. Earlier we have suggested a method to implement the layer-oriented approach, and in view of recent concerns we now explain the proposed scheme in further detail. We note that in any layer-oriented system, one sensor is conjugated to the pupil and the others are conjugated to higher altitudes. For the latter the sensing surface is illuminated by only part of the field-of-view. Nighttime layer-oriented systems correct for this field reduction in terms of the pyramid sensors, which indicate the phase shift directly. Their successful implementation shows that the field reduction is no crucial limitation. In the solar approach the images recorded behind the Shack-Hartmann sub-apertures are vignetted due to the field reduction, and here this can be accounted for by a suitable adjustment of the algorithms to calculate the local wave-front slopes. A further concern we dispel relates to the optical layout of a layer-oriented solar system. © 2014 Optical Society of America

*OCIS codes:* 110.0115, 110.1080

## 1. Introduction

High angular resolution of the solar surface over large fields-of-view is needed to understand the behavior of the solar magnetic fields. This calls for MCAO correction on ground-based solar telescopes [1]. In MCAO systems, the use of several deformable mirrors permits correction of the wavefront distortions within larger fields-of-view. Within MCAO there are fundamentally two different approaches – *star-oriented* and *layer-oriented*. Up to now, solar

MCAO uses exclusively a star-oriented approach where each sensor measures the integrated wavefront distortions along a specific direction. Adequate inference of the 3D turbulence from measurements along a few discrete directions is, however, a highly ill-conditioned problem, and large field-sizes are thus difficult to correct. The field size is limited to approximately 60 arc seconds [2], while fields of several arc minutes are required to observe the formation and evolution of solar spots. We have recently proposed a layer-oriented set-up for solar adaptive optics (AO) [3]. In this approach, the wavefront distortions are averaged over a wide-field: the signal from distant turbulence is attenuated and the tomographic reconstruction is achieved optically.

Analyzing the layer-oriented MCAO approach for solar observations Marino & Woger [4] have suggested that the method is not viable due to vignetting. We appreciate their effort and take the opportunity to give further details on the layer-oriented method.

A difficulty inherent to any layer-oriented MCAO approach is that sensors conjugated above the telescope pupil (to a so-called *meta-pupil*) are not illuminated by the entire field-of-view. This field-reduction limits the attenuation of the signal from unconjugated layers. Nighttime layer-oriented systems employ pyramid sensors [5]. A few pyramids map the average phase from the reduced field of view on the conjugated layer. Because pyramid sensors produce pupil images rather than field images, the field reduction does not become visible, but the successful use of the system shows that the field reduction is not a crucial limitation. In the solar approach the lenslets of the Shack-Hartmann (SH) wavefront sensor produce field images which are then intercorrelated to determine the average phase shifts in the conjugated layer [3]. The field reduction becomes apparent as vignetting in these images. But the limitation due to the field reduction is the same as in the night time system. We discuss this aspect in Section 2.

As expected in a new approach, adjustments of existing data-analysis techniques are required, and in our case the adjustment can be achieved in two ways. When the sub-aperture in the center of the pupil is not vignetted, it can be used as a reference for the cross-correlation of the sensor images. The reference merely needs to be multiplied by a masking function that accounts for the transmission in dependence on field-direction. The cross-correlation then proceeds in the standard way. When the central sub-aperture image is vignetted, each sub-aperture image can be cross-correlated against itself: an image recorded at time  $t$  is cross-correlated against an image recorded at time  $t_0$ . One retains a static aberration, but to correct for it one can use the fact that the mean slope introduced by atmospheric turbulence is zero. This is discussed in Section 3.

As a further concern about the feasibility of the set-up it has been suggested that large fields require impractically small focal lengths [4]. Section 4 clarifies that this conclusion relies on the (unnecessary) assumption of a fixed *pitch*, i.e. size, of the SH lenslets. With

variable lenslet pitch, the focal length can be sufficiently large and detector pixels of equal size can be utilized.

## 2. Field reduction in layer-oriented systems

The layer oriented method benefits from large fields, because they attenuate the signal from distant layers more efficiently [3]. On the other hand, for wavefront sensors that are conjugated above the telescope pupil the sensing can not extend over the entire field-of view: Let  $A$  be a point on a meta-pupil (i.e. on a plane above the telescope pupil). The local wavefront slope at point  $A$  can be sensed only on those parts of the wavefronts that experience the distortion at point  $A$ . Since for certain directions no part of the wavefront crosses point  $A$ , these directions can not contribute to the determination of the distortion introduced at point  $A$ .

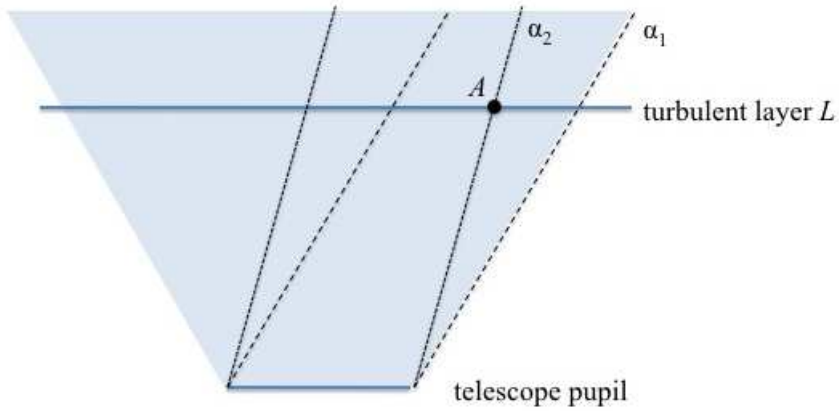


Fig. 1. A distortion introduced at point  $A$  is experienced only by wavefronts within directions  $\alpha_1$  to  $\alpha_2$ . Hence only a reduced part of the field can be used to sense the distortion introduced at point  $A$ . This is independent of the particular sensing method used: the field-of-view reduction affects pyramid-based systems in the same way as it affects SH-based systems.

This reduction of the field-of-view is inherent to any layer-oriented system and it affects pyramid-based systems in quite the same way as it affects SH sensors. Consider the diagram of Fig. 1: the distortion introduced at point  $A$  is experienced only by wavefronts within the directions  $\alpha_1$  to  $\alpha_2$ . The distortion is not experienced in other directions (to the left of  $\alpha_2$ ): whatever sensor is used – pyramids, SH or any other – only the reduced field ( $\alpha_1$  to  $\alpha_2$ ) can be used to sense the distortion introduced at point  $A$ .

In a pyramid-based system, the detector is conjugated to the high-altitude layer. This is optically equivalent to placing the detector in plane  $L$  of Fig. 1: a detector pixel at point  $A$  receives light from within  $\alpha_1$  to  $\alpha_2$ . It does not receive light from directions to the left of  $\alpha_2$ : the field that is used for the sensing is thus limited. In the same way, the lenslet array of a SH based system is conjugated to plane  $L$ , and a lenslet at point  $A$  therefore receives light only from within  $\alpha_1$  to  $\alpha_2$ .

The attenuation of a signal from unconjugated layers is substantially more efficient on a solar image than on a nighttime image. This is so because the averaging relates to a continuous field, rather than a discrete number of directions. In nighttime systems, the number of field directions is restricted by the number of guide-stars within the field and typically it lies between 3 and 8 [6]. Nevertheless, nighttime layer oriented adaptive-optical correction has been shown to work [6]. Since the field-reduction in high-altitude conjugation affects solar systems equally, it will likewise not impede their performance.

In [3] it was suggested that very wide fields are required to sufficiently attenuate the signal from distant layers. We considered the criterion that the signal from distant layers should lie below the fitting error of the deformable mirror, but noted that the AO correction might still be successful on smaller fields, because the signal from a layer at height,  $h$ , is strongest on the sensor,  $S$ , whose conjugate height is closest to  $h$ . The layer may still generate substantial signal on other sensors, but these signals are weaker than the signal on sensor  $S$ . Sensor  $S$  is thus best at correcting distortions at height  $h$ , and it therefore takes over the correction. This principle is inherent to a layer-oriented AO correction. It has been successful on nighttime AO systems, where the field attenuation is substantially less than in solar based systems – see the discussion above. We conclude that the criterion outlined in [3] is unnecessarily conservative for a closed loop AO correction; it is more appropriate for the design of an instrument that measures atmospheric profiles without adaptive-optical correction.

In conclusion, at high altitude, some of the turbulence is not experienced by the entire field-of-view (because the distortion occurs outside the pupil). Therefore one cannot use the entire field to sense all of the high-altitude turbulence. This is wholly independent of the particular sensing method used. Since pyramid based systems have been demonstrated on-sky, the field-reduction will likewise be no crucial limitation in the solar layer-oriented system.

### 3. Vignetting

A feature specific to the use of SH wavefront sensors is the vignetting of the images behind the lenslets. This affects the cross-correlation and it has been argued [4] that “this is particularly problematic for sub-apertures on opposite edges, which share no common un-vignetted field points. These effects make the successful cross-correlation of sub-aperture images a practical

impossibility.”

First, one notes that there is no need to cross-correlate sub-aperture images recorded on opposite edges of the pupil. In a conventional AO system, the image recorded behind a sub-aperture  $i_0$  at time  $t_0$  is used as reference and is cross-correlated against all sub-aperture images recorded at times  $t > t_0$ . The reference image is regularly updated, typically every 30 seconds. Sub-aperture  $i_0$  is chosen near the center of the pupil, since instrumental aberrations are usually smallest at the center of the pupil. A second possibility is to cross-correlate each sub-aperture image against itself: an image recorded at time  $t$  behind sub-aperture  $i$  is cross-correlated with an image recorded at time  $t_0$  behind the same sub-aperture  $i$ . In neither case is there a need to cross-correlate images recorded at opposite edges of the pupil.

Three familiar approaches confute the asserted impossibility to cross-correlate vignetted sub-aperture images [4]:

1. If the central sub-aperture is not vignetted, it can be used as reference and can be cross-correlated against all other sub-aperture images, a masking function on the reference image is sufficient. The masking function accounts for the vignetting: it equals 0 where the field direction is entirely vignetted, and 1 where it is not.

Let  $D$  be the telescope diameter,  $d$  the sub-aperture diameter and  $h$  the conjugate height of the sensor. The central sub-aperture is not vignetted if the field diameter remains within:

$$\alpha \leq \frac{D - d}{h} \quad (1)$$

Assume a sub-aperture diameter  $d = 0.1$  m. For the next generation of 4 m class solar telescopes and field-diameters of 100”, the central sub-aperture is not vignetted if the wavefront sensor is conjugated below 8 km. The central sub-aperture can then be used as reference.

2. For larger fields-of-view and/or higher conjugate heights the above method is not applicable, but one can then cross-correlate each sub-aperture against itself (an image recorded at time  $t$  against an image recorded at time  $t_0$ ). One retains a static wavefront distortion but can correct it since the mean slope due to atmospheric turbulence is zero. No masking function is then required.
3. If the SH wavefront sensors have the same field-of-view and pixel scale, one could use an image of the ground-layer sensor as reference for the high-altitude sensors. This relies on the perfect alignment between sensors which is essential at any rate for successful MCAO correction. In this approach one applies again a direction-dependent masking function that accounts for vignetting.

In conventional solar AO systems, the cross-correlation extends over typically  $16 \times 16$  pixels. As long as the vignetted image spans  $16 \times 16$  pixels, the cross-correlation will therefore be of sufficient quality [7]. The main point is to define a proper reference image.

As shown in sections 2 and 3, vignetting is a manageable complication of layer oriented solar MCAO. The main difficulty appears to be the need for very large and fast detectors, in order to achieve the essential advantage of the method: the use of the full field information.

#### 4. Consideration of the optical set-up

A further concern that can be addressed is the claim that – in a layer-oriented system – large fields require lenslet arrays with impractically small focal lengths [4]. A lenslet array of pitch  $p$  and focal length  $f$  can image a maximum field diameter:

$$\alpha = \frac{p^2 N}{f D} \quad (2)$$

where  $D$  is the diameter of the telescope pupil and  $N$  equals the number of sub-apertures across the beam diameter. From this relation it has been concluded that, for a given pitch, short focal lengths are required to image large fields of view [4].

However there is no need to keep the lenslet pitch constant. Let  $s$  be the size of the detector pixels. The cross-correlation of solar images requires an angular sampling  $\theta \leq 0.5''$ . The pitch is related to the field diameter through the relation:

$$p = s \frac{\alpha}{\theta} \quad (3)$$

The number of sub-apertures across the beam-diameter equals  $N = D/d$ , where  $d$  is the sub-aperture diameter. Hence, Eq. 2 is rewritten as:

$$f = \frac{s^2 \alpha}{d \theta^2} \quad (4)$$

For a given pixel size, the focal length of the lenslets increases with the field diameter. There is thus no basis for the objection that large field sizes require lenslets with impractically small focal lengths.

Fig. 2 traces the focal length and pitch value as a function of field diameter, for a pixel size  $s = 7 \mu\text{m}$ , an angular sampling  $\theta = 0.5''$  and a sub-aperture diameter  $d = 0.1 \text{ m}$ . Both the focal length and the pitch increase with field size. Note that large pitch values facilitate the optical alignment and thereby improve the image quality.

#### 5. Conclusion

In a layer-oriented adaptive optics system, a deformable mirror and a wavefront sensor are each conjugated to one dominant turbulent layer. For the sensors conjugated to the

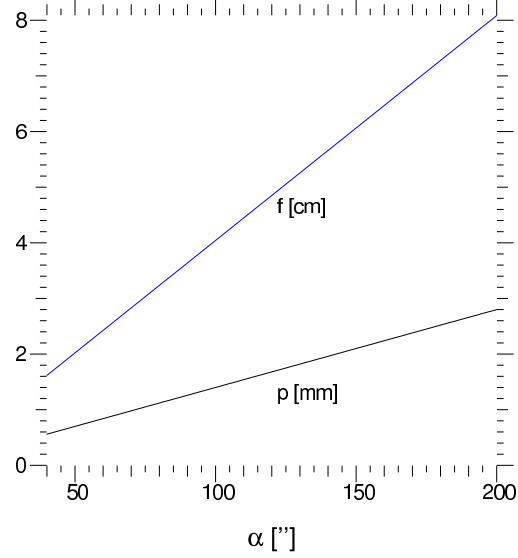


Fig. 2. The pitch,  $p$ , and focal length,  $f$ , of a SH lenslet array as a function of the field diameter  $\alpha$ , for a  $7\mu\text{m}$  pixel size,  $0.5''$  pixel sampling and  $0.1\text{ m}$  diameter sub-apertures.

higher turbulent layers, the sensing surface is only illuminated by part of the field-of-view. In a pyramid-based system not every detector pixel is illuminated by the entire field of view, and likewise in a SH-based system not every lenslet is illuminated by the entire field. This reduction of the field-of-view limits the signal attenuation from distant layers. It is a constraint inherent to the layer-oriented approach, and does not depend on the type of wavefront sensor.

Nighttime based layer-oriented systems are being successfully used on-sky. The solar application has the added advantage that the attenuation of distant layers is considerably more efficient since the signal is averaged over a continuous field, rather than a limited number of directions [5,6]. The field reduction must therefore be even less critical than in the nighttime systems.

In the solar application the field-reduction is directly noticeable because it causes the images behind the SH sensors to be vignetted. This requires a slight but straightforward adjustment of the algorithms to determine the local wavefront slopes. If the sub-aperture in the center of the pupil is not vignetted, it can be used as reference. It needs to be multiplied with a masking function that equals 1 where the image is not vignetted and 0 where the image is entirely vignetted. The cross-correlation can then be done in terms of standard functions. For large fields and high conjugated altitudes, even the central sub-aperture may

be vignetted. In this case, one can cross-correlate each sub-aperture against itself – images recorded at times  $t$  against an image recorded at time  $t_0$ . No masking function is then required and the correlation algorithms used in solar AO can be applied directly. As mentioned, one retains a static aberration which can be corrected since the average slope induced by the atmosphere equals zero.

On the implicit assumption of a constant lenslet pitch, it has been claimed that lenslet arrays with excessively small focal lengths are needed on large fields-of-view [4]. However, if detector pixels of constant size are used, the focal length of the lenslets increases with field size and the lenslet pitch increases likewise. As it happens, this facilitates system alignment and thereby improves image quality.

In conclusion, field-reduction is inherent to any layer-oriented approach and is no critical limitation. The specific complication of vignetted SH images can be accounted for by standard methods. The main difficulty of the new layer oriented multi-conjugate adaptive optical system is the need for fast detectors with a large number of pixels. If this is a limitation today, technological advances will resolve it before long.

## References

1. M. Collados Vera and EST Team. Instrumental Capabilities of the EST. In T. R. Rimmele, A. Tritschler, F. Wöger, M. Collados Vera, H. Socas-Navarro, R. Schlichenmaier, M. Carlsson, T. Berger, A. Cadavid, P. R. Gilbert, P. R. Goode, and M. Knölker, editors, *Second ATST-EAST Meeting: Magnetic Fields from the Photosphere to the Corona.*, volume 463 of *Astronomical Society of the Pacific Conference Series*, page 413, December 2012.
2. T. Berkefeld, D. Soltau, D. Del Moro, and M. Löfdahl. Wavefront sensing and wavefront reconstruction for the 4m European Solar Telescope EST. In *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, volume 7736 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, July 2010.
3. A. Kellerer. Layer-oriented adaptive optics for solar telescopes. *Appl. Opt.*, 51(23):5743–5751, Aug 2012.
4. J. Marino and F. Wöger. Feasibility study of a layer-oriented wavefront sensor for solar telescopes. *Appl. Opt.*, 53(4):685–693, Feb 2014.
5. R. Ragazzoni, J. Farinato, and E. Marchetti. Adaptive optics for 100-m-class telescopes: new challenges require new solutions. In P. L. Wizinowich, editor, *Adaptive Optical Systems Technology*, volume 4007 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, pages 1076–1087, July 2000.
6. C. Arcidiacono, M. Lombini, A. Moretti, R. Ragazzoni, J. Farinato, R. Falomo, M. Gulieuszik, and G. Piotto. An update of the on-sky performance of the layer-oriented wave-



- front sensor for MAD. In *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, volume 7736 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, July 2010.
7. M. G. Löfdahl. Evaluation of image-shift measurement algorithms for solar Shack-Hartmann wavefront sensors. *AOA*, 524:A90, December 2010.